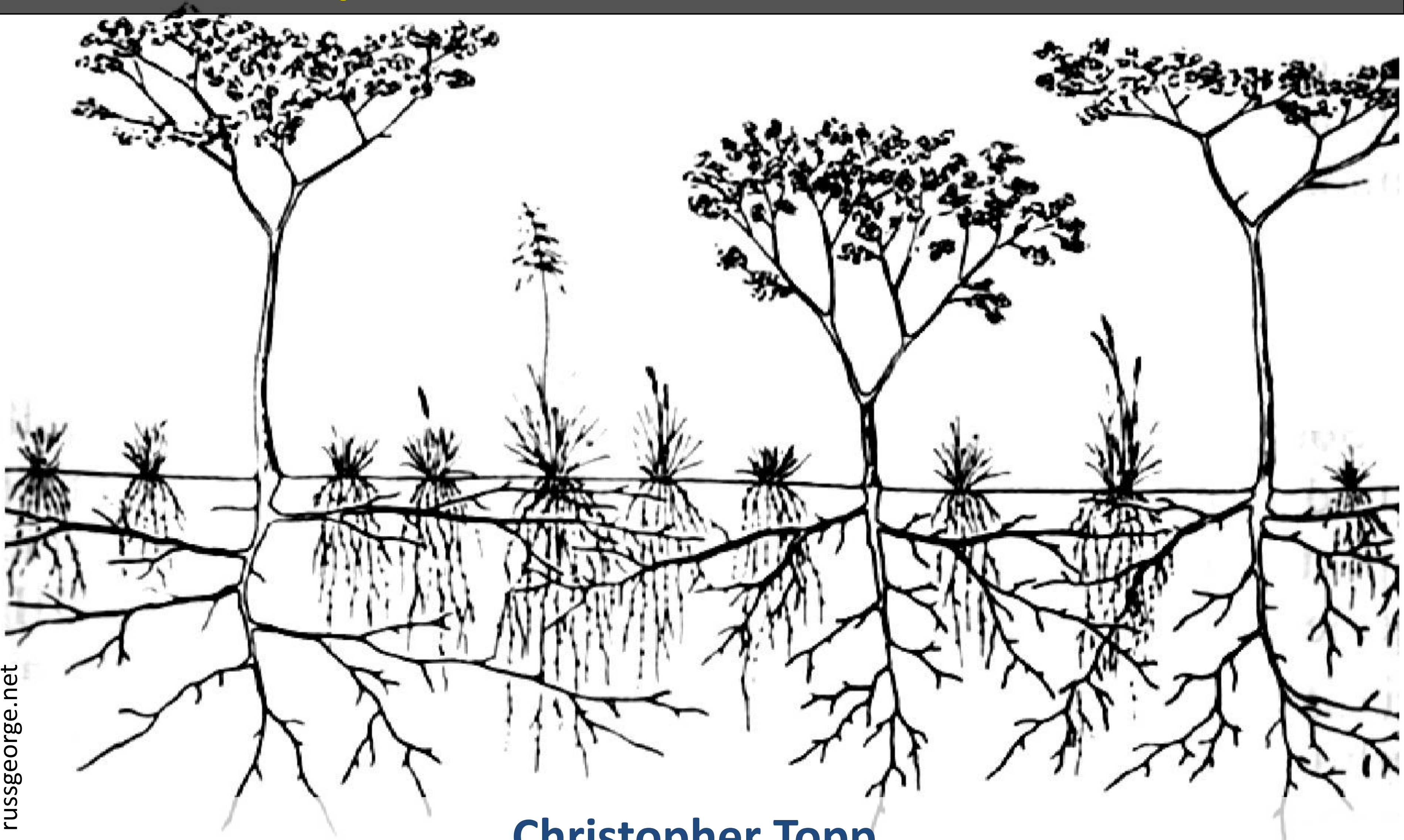
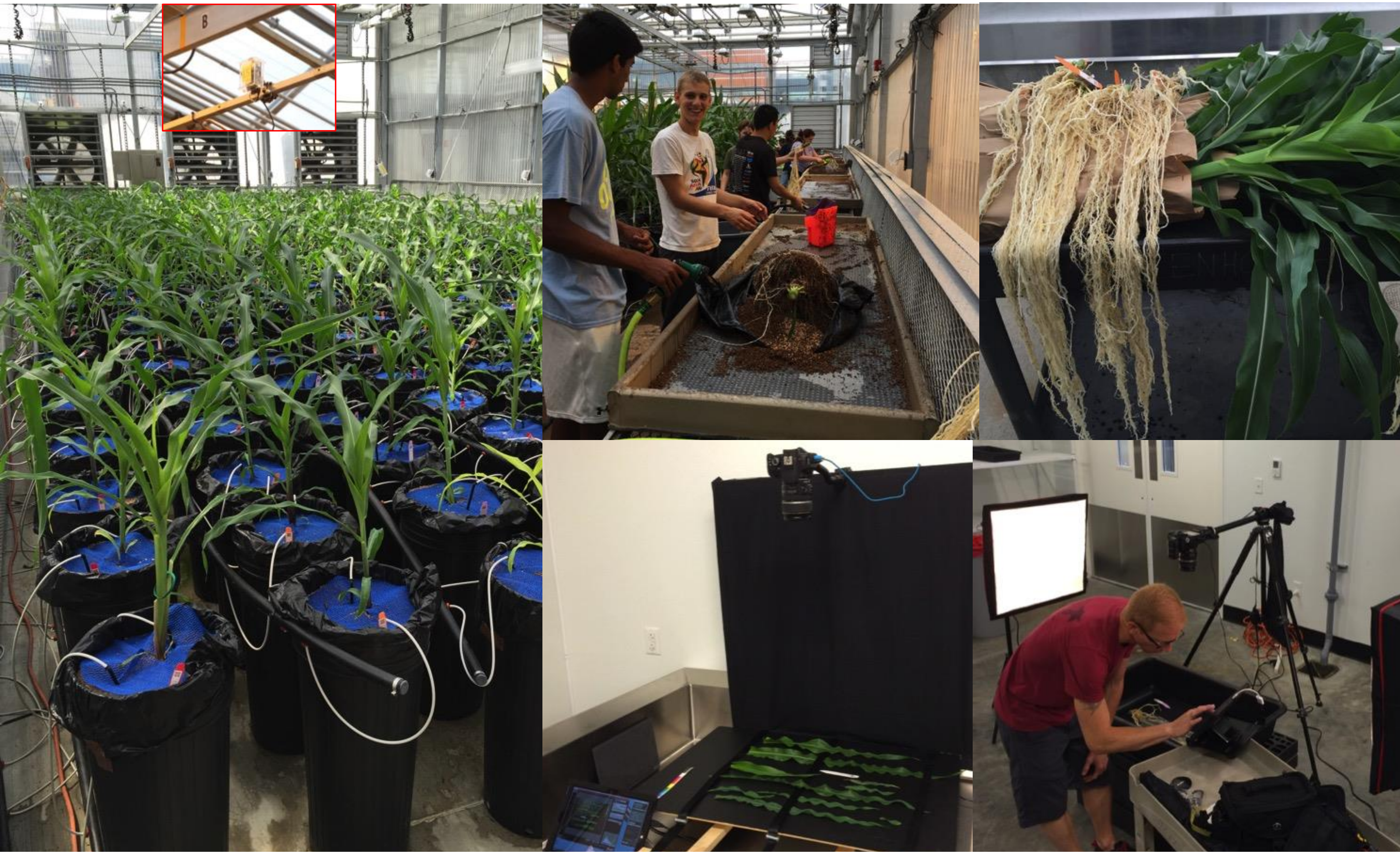
Towards an integrated understanding of the plant and plant-environment interactions



Christopher Topp
Donald Danforth Plant Science Center

How do we study the plant as an integrated system?

How do we study the plant as an integrated system?



root and shoot phenotyping in controlled environments

Todd Mockler and Topp Labs

Plant phenomics is relatively nascent; we lack expertise in tool development, data processing and analysis

Two groups we need to forge relationships with:

medical imaging and industrial phenotyping

1. embed plant phenotyping at medical schools

   → **advanced imaging tools (X-ray CT, PET, Spectroscopy, etc.)**

2. leverage advances in production agriculture for science

   → **robotics for throughput and precision**

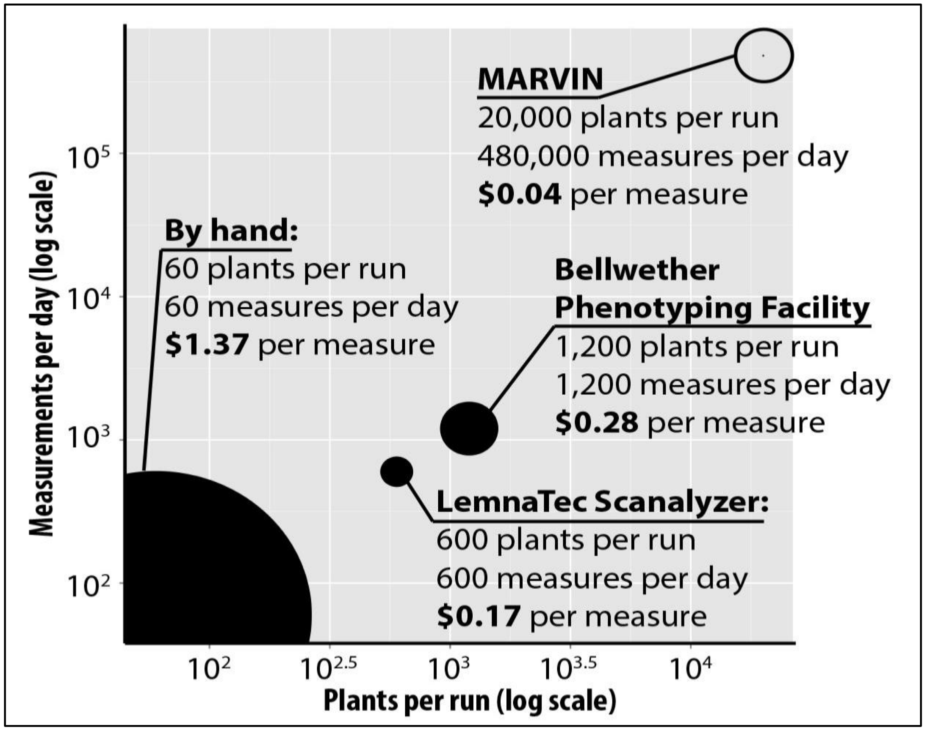
3. technology moves fast

   → **focus on open source tools and flexible platforms**

We can leverage existing technologies in industrial engineering, robotics, computer vision/AI

MARVIN: Rick van de Zedde, Wageningen University, Netherlands

High Throughput Phenotyping



1. Build a versatile, ultra-throughput platform capable of exploring the growth and environmental response in the world's germplasm

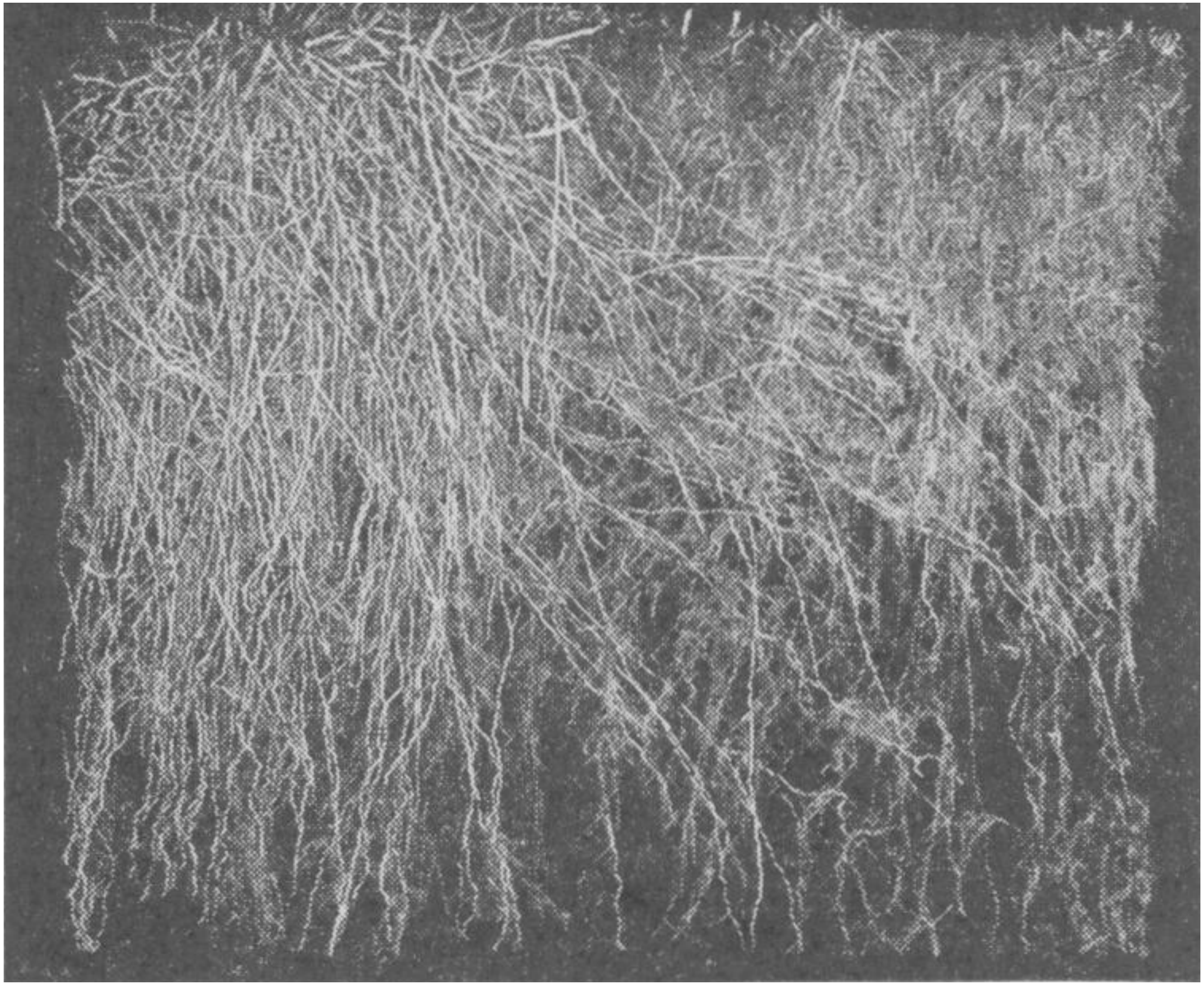
1. Analytic capabilities to interpret unprecedented architectural data from the root and shoot and place this into a genetic framework

2. Test specific hypotheses concerning whole plant architecture, the developmental constraints of yield and biomass accumulation, and high resolution time lapses of plant responses to stresses and competitors

Dan Chitwood | Toby Kellogg | Chris Topp | @ Danforth Center

How do we study the plant as an integrated system?

Roots are often the bottleneck



Weaver and Voigt Botanical Gazette 1950

Identifying the genetic and functional basis of root architecture: integrated root phenotyping with quantitative genetics

Root phenotyping methods **X** High-resolution germplasm with important agronomic traits

Environmental control

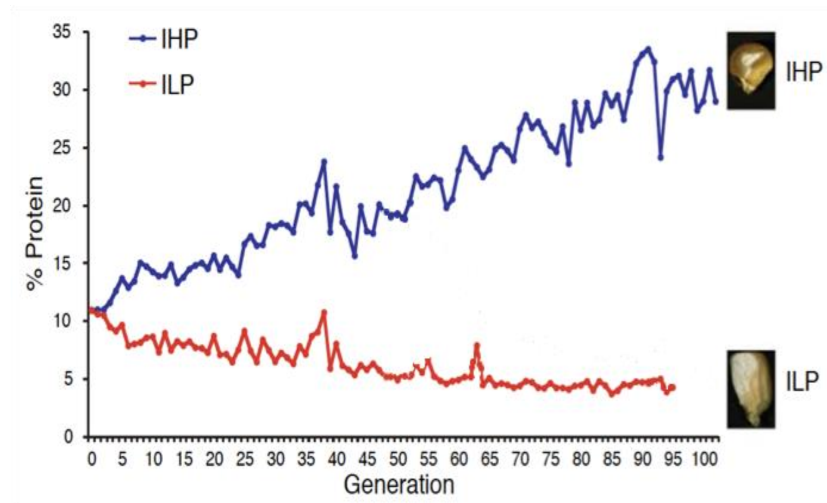
Agricultural relativity

1. 3D hydroponic, gel, sand, turface imaging

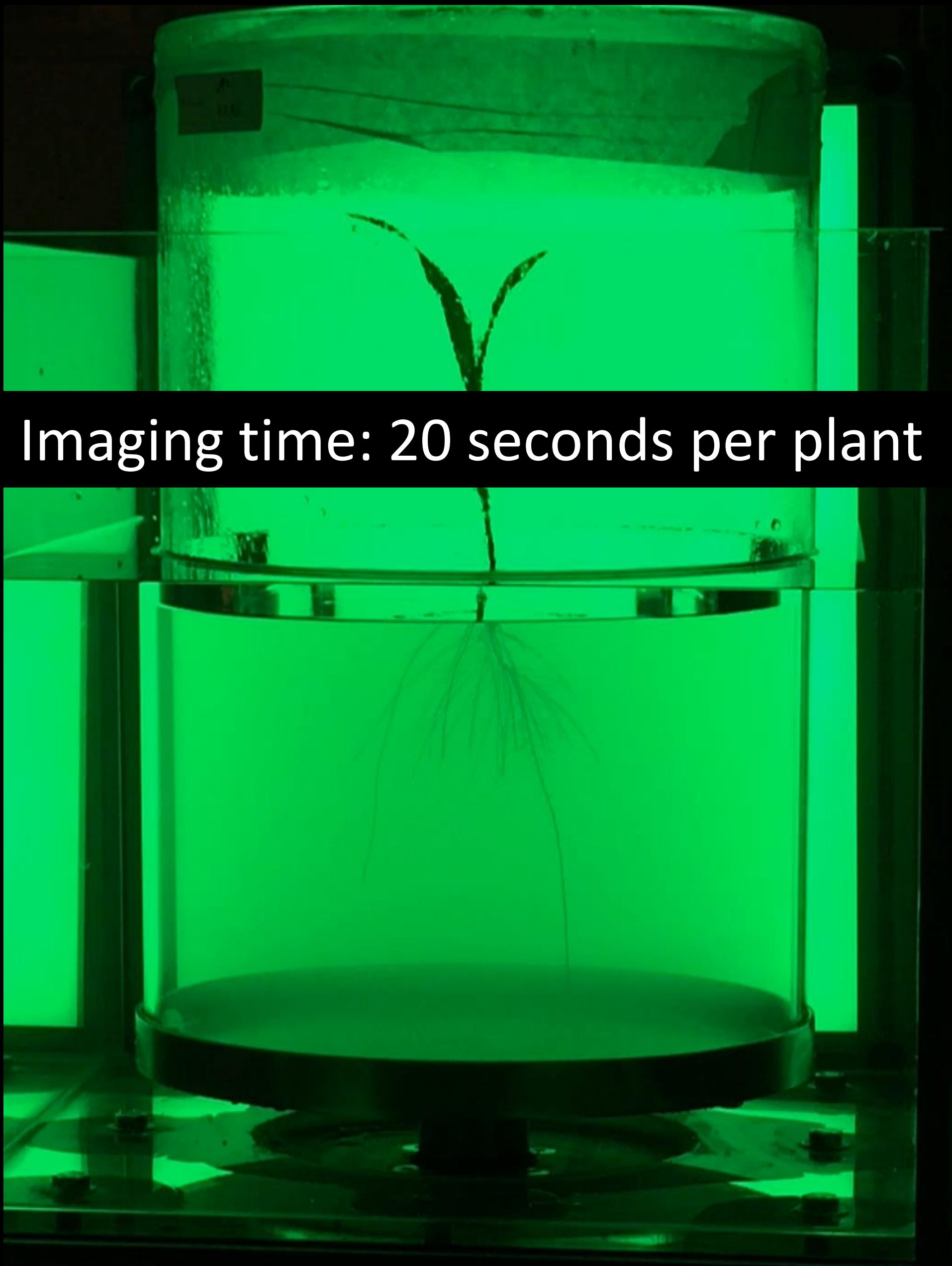
2. PET and/or X-ray CT in pots

3. Image analysis of excavated root crowns from the field – optical 2D and X-ray 3D

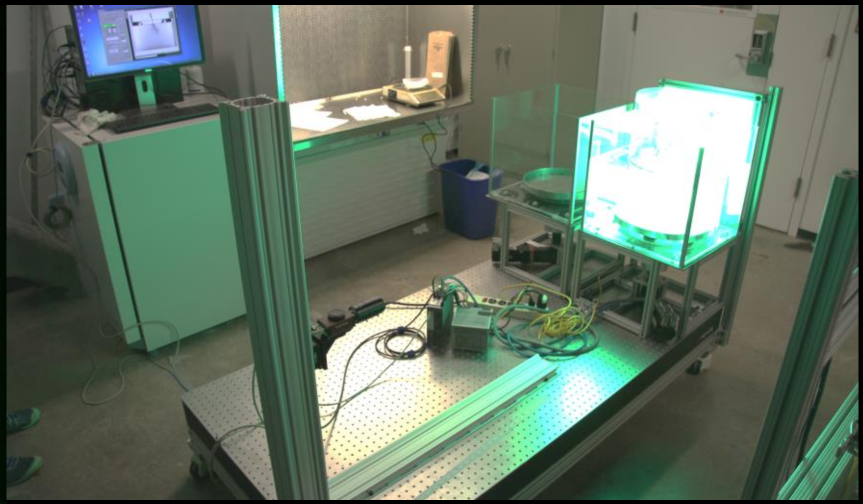
4. Mini-rhizotrons, X-ray CT soil cores or other developing in situ phenotyping methods (GPR, THz)

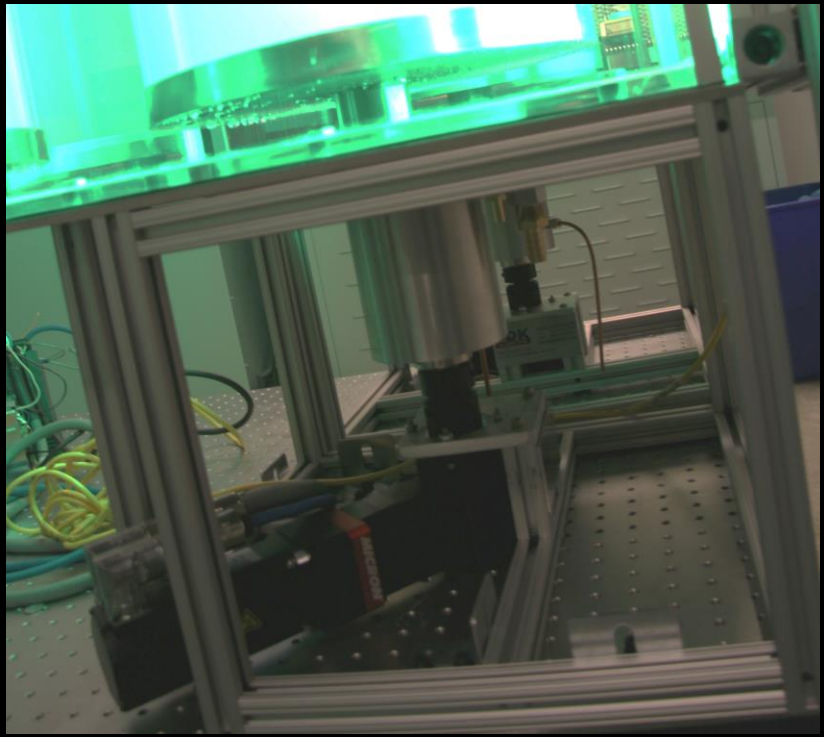


Optical Projection Tomography (OPT) platform for root phenotyping in 3D

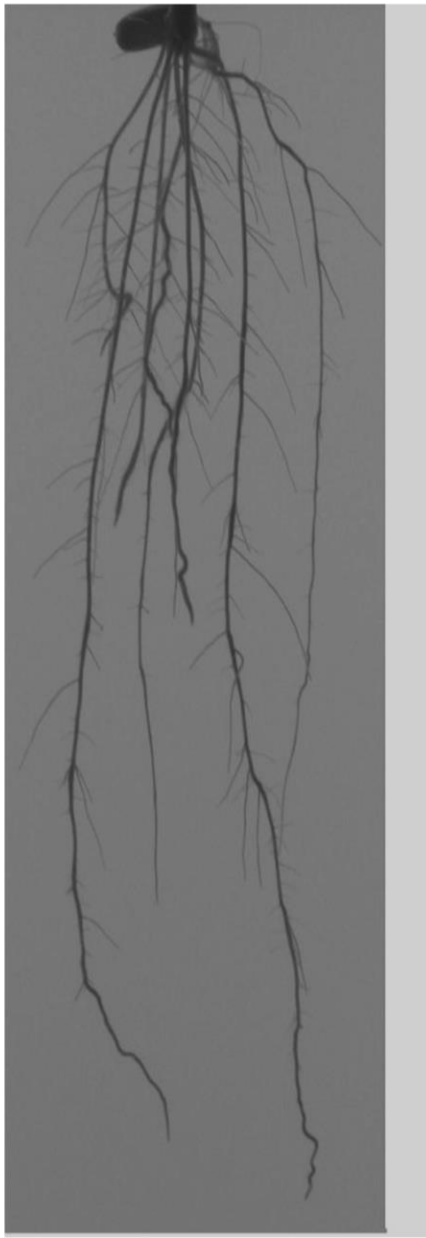


Imaging time: 20 seconds per plant





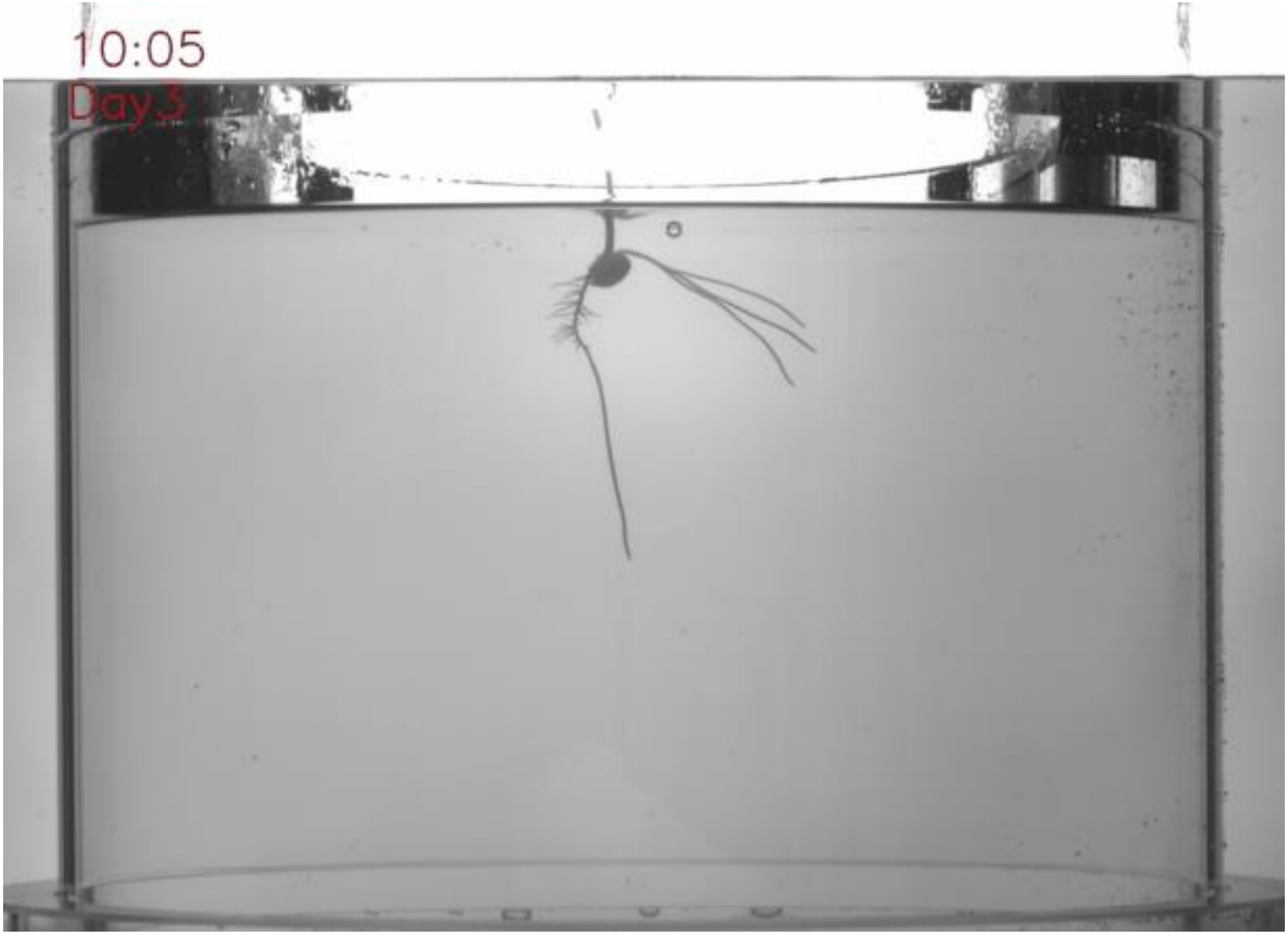
3-dimensional modelling of root architecture



traits analyzed in 3D

1. median root number
2. maximum root number
3. root system volume
4. convex hull volume
5. solidity
6. surface area
7. bushiness
8. total root length
9. root system volume
10. specific root length
11. number of branches
12. et al.

Rootwork - Zheng et al ICCV 2011
RootReader3D - Clark et al Plant Physiology 2011
RSA-Gia pipeline – Topp et al PNAS 2013



Capturing the **time dimension** is key to understanding how roots interact with the environment

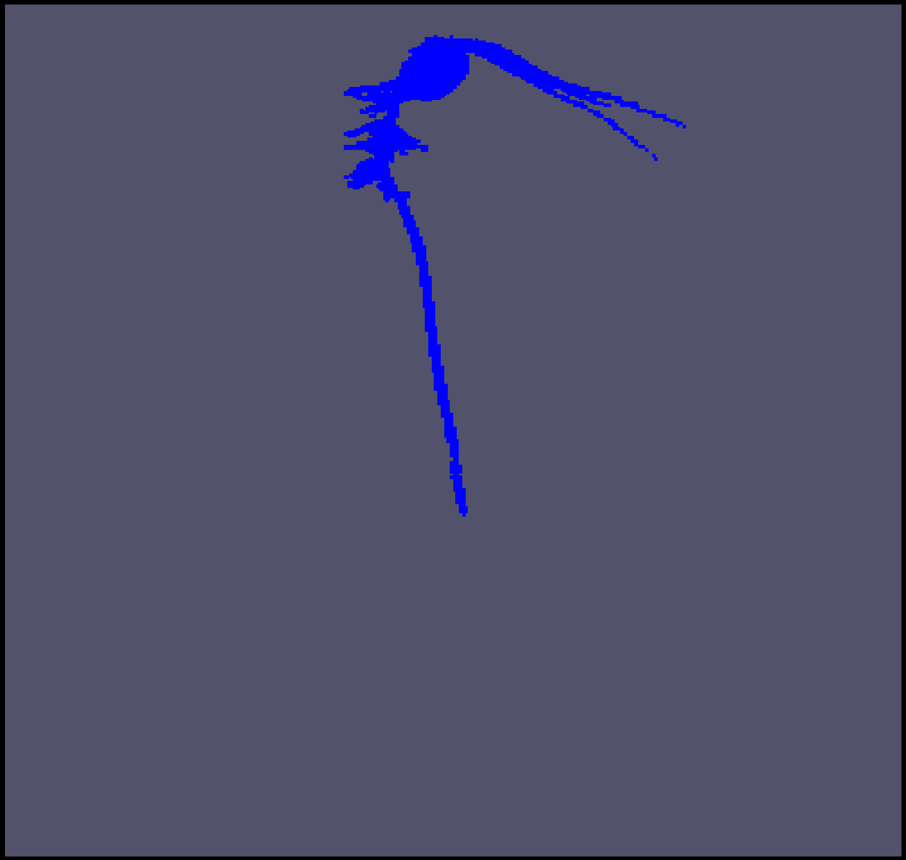
DynamicRoots: 3D time series analysis software

For each root at each time point:

topological order, length, width, volume, angles, curvature, etc

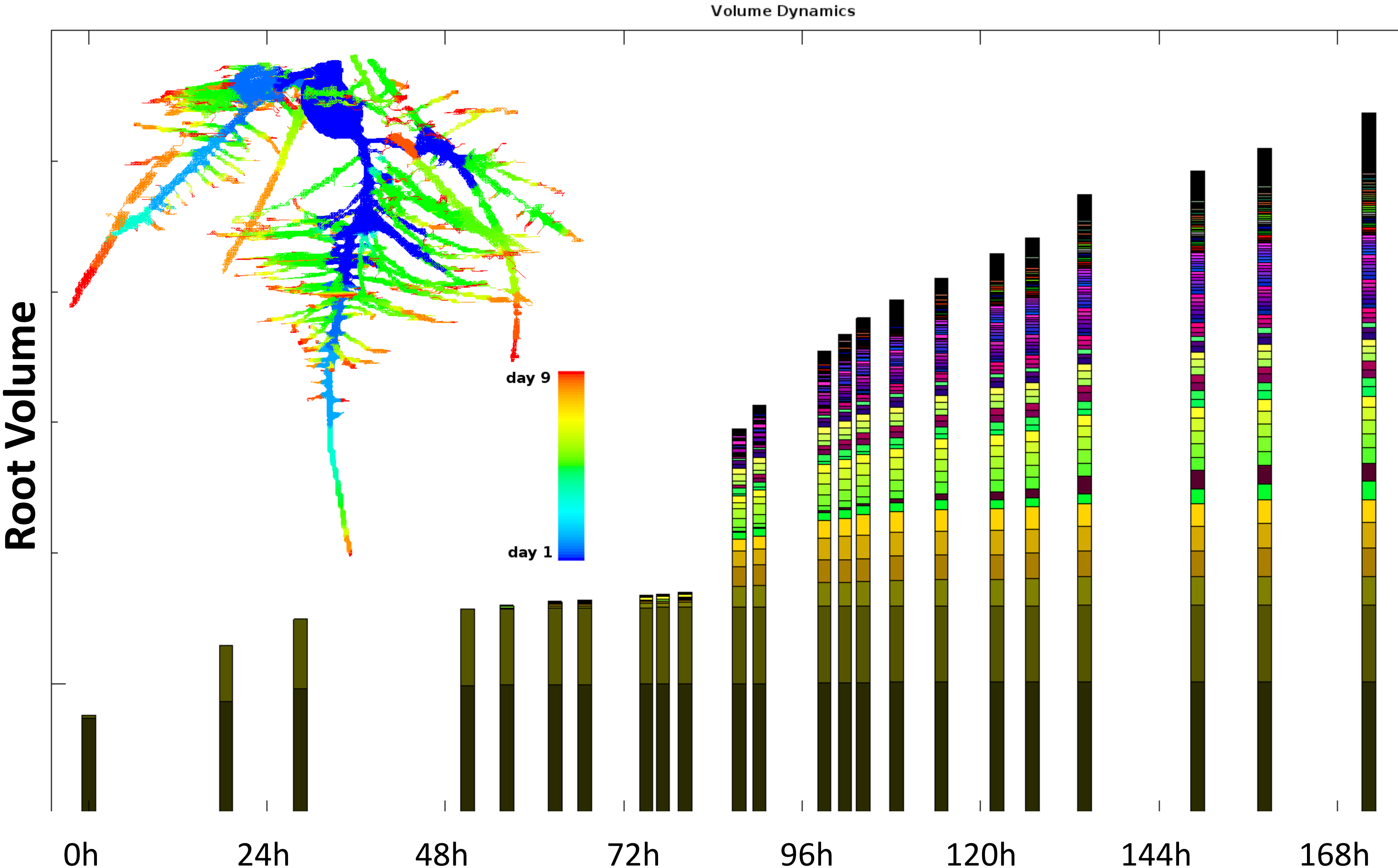
For some or all roots at one time or as a function of time:

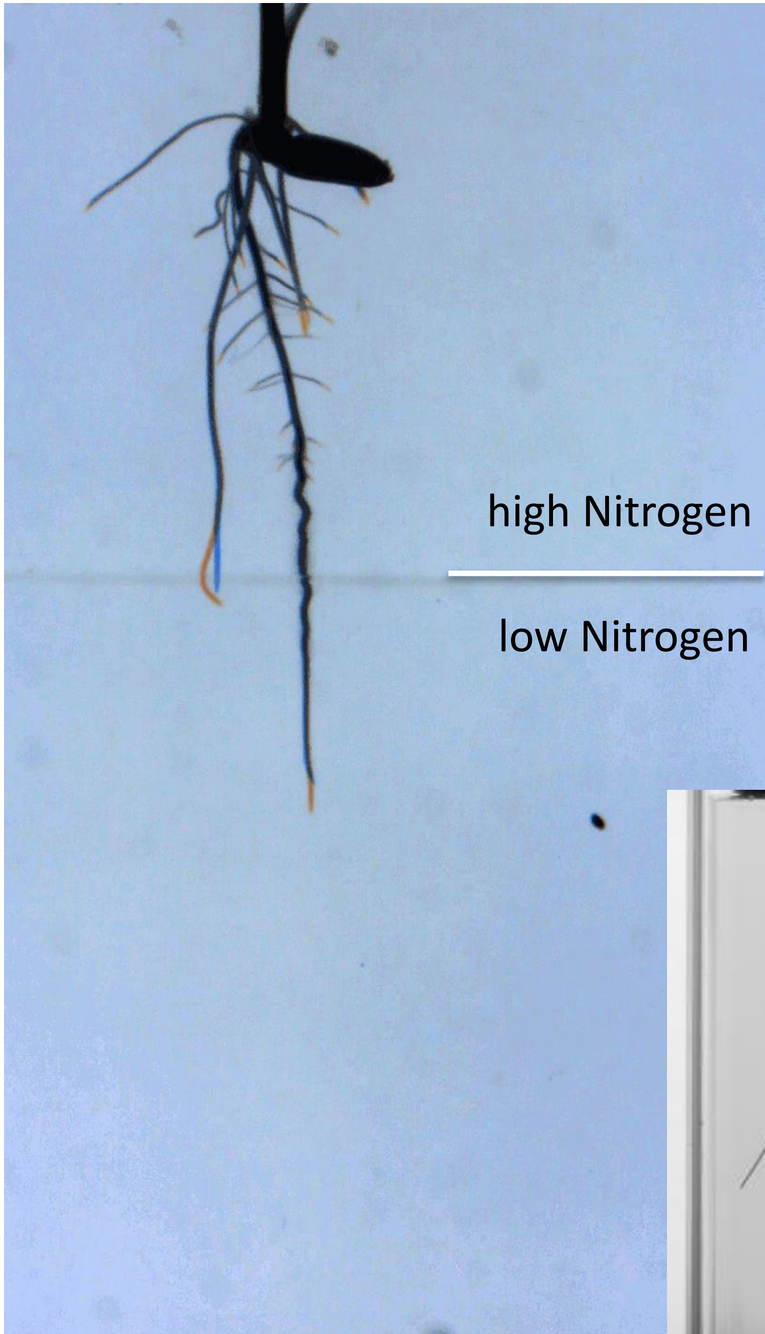
entire RSA topology, depth distributions, emergence and tip angles, dynamic curvatures, behavior in XYZ defined ROIs, etc.



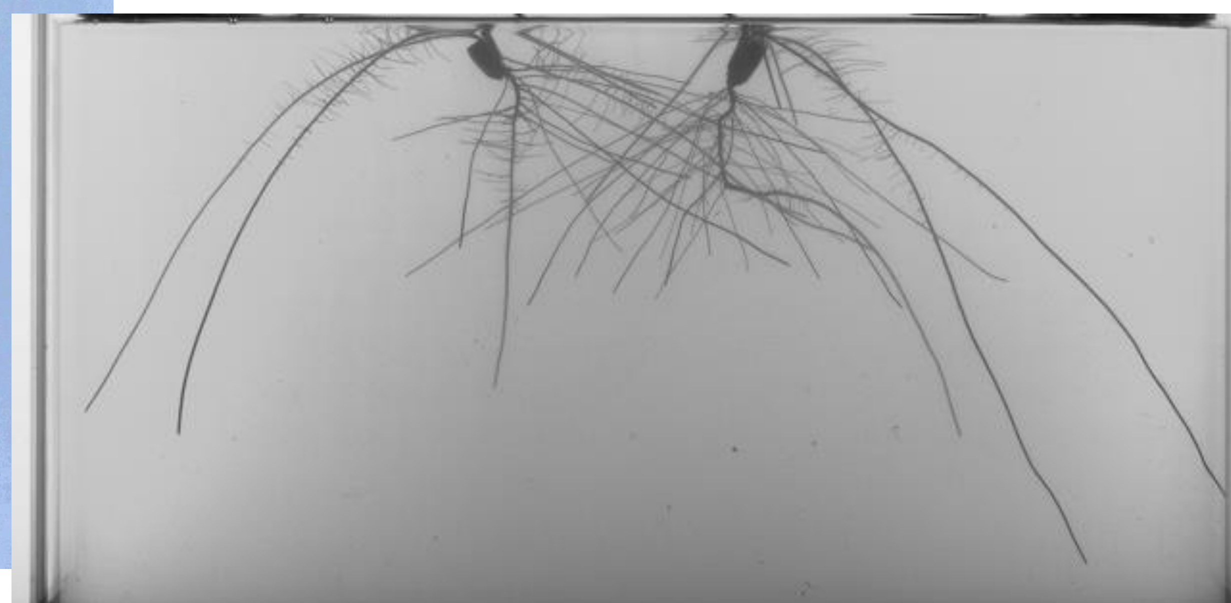
Olga Symonova, Chris Topp, and Herbert Edelsbrunner; PLoS ONE 2015

Dynamic Roots: per branch measurements of root growth over time





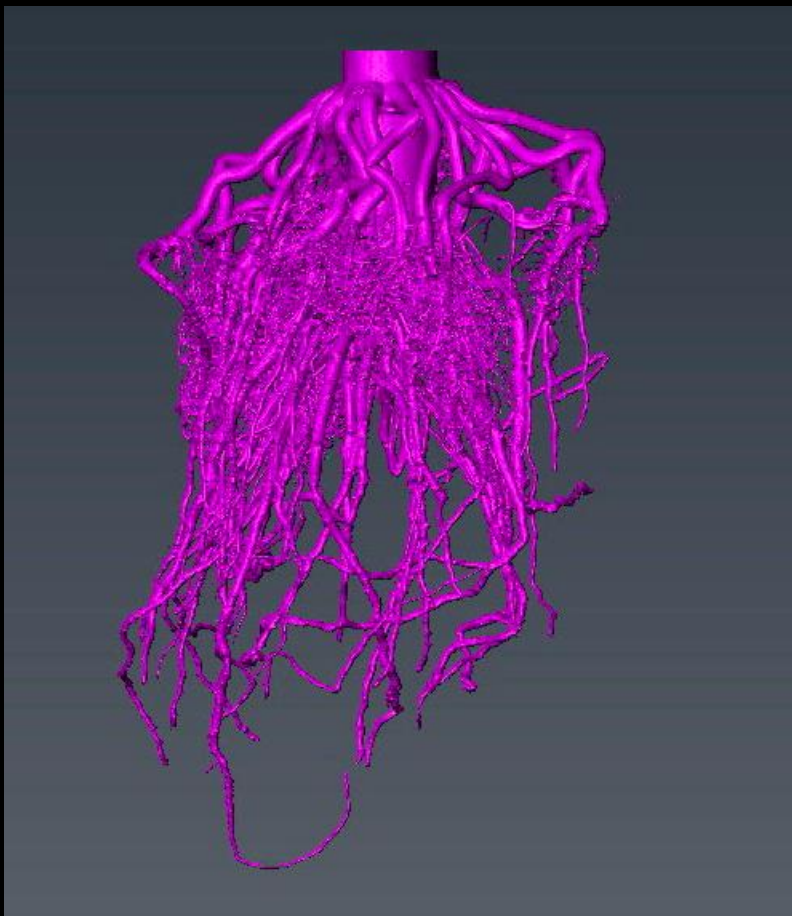
What are the processes driving root growth under different environmental stimuli?



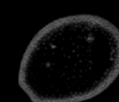
X-ray Computed Tomography:

a medical and industrial workhorse that can be used for plant science

X-ray CT can be used to extract fine-resolution information from complicated architectures in high-throughput

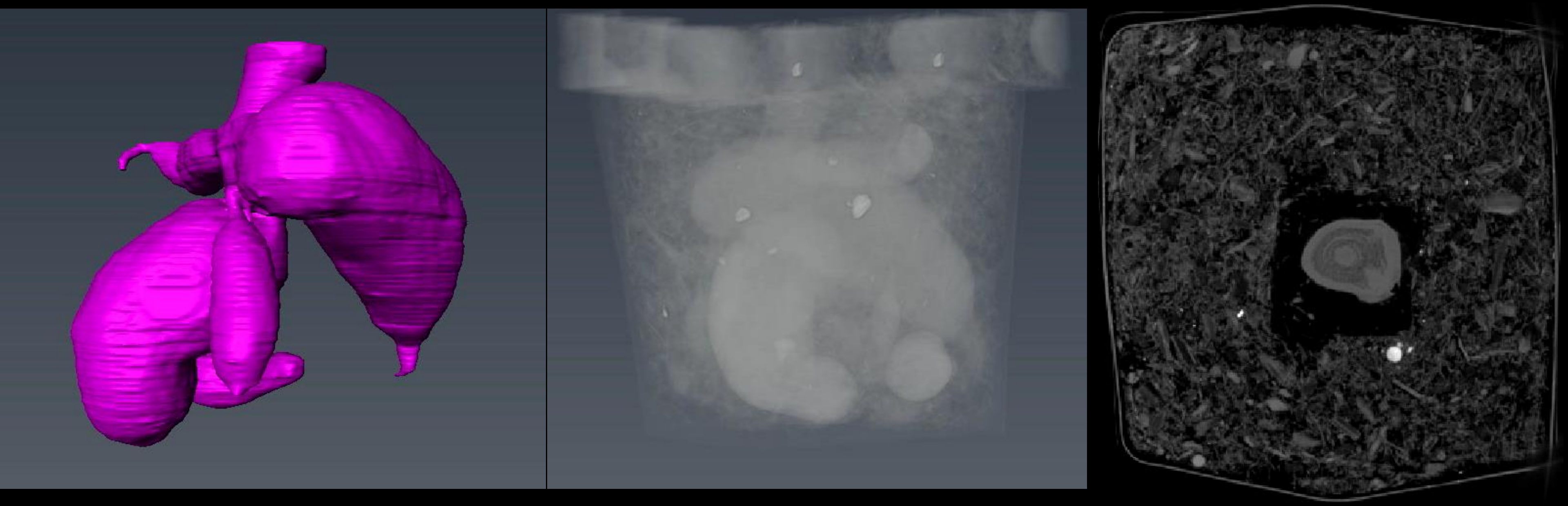


X-Ray CT scanned excavated root crown
scan time ~ 2 minutes
resolution 110 micron



Volume	0.9 x 10^6
Convex Volume	14 x 10^6
Solidity	0.0661
Depth	433
Total Length	74,486
# tips	1284

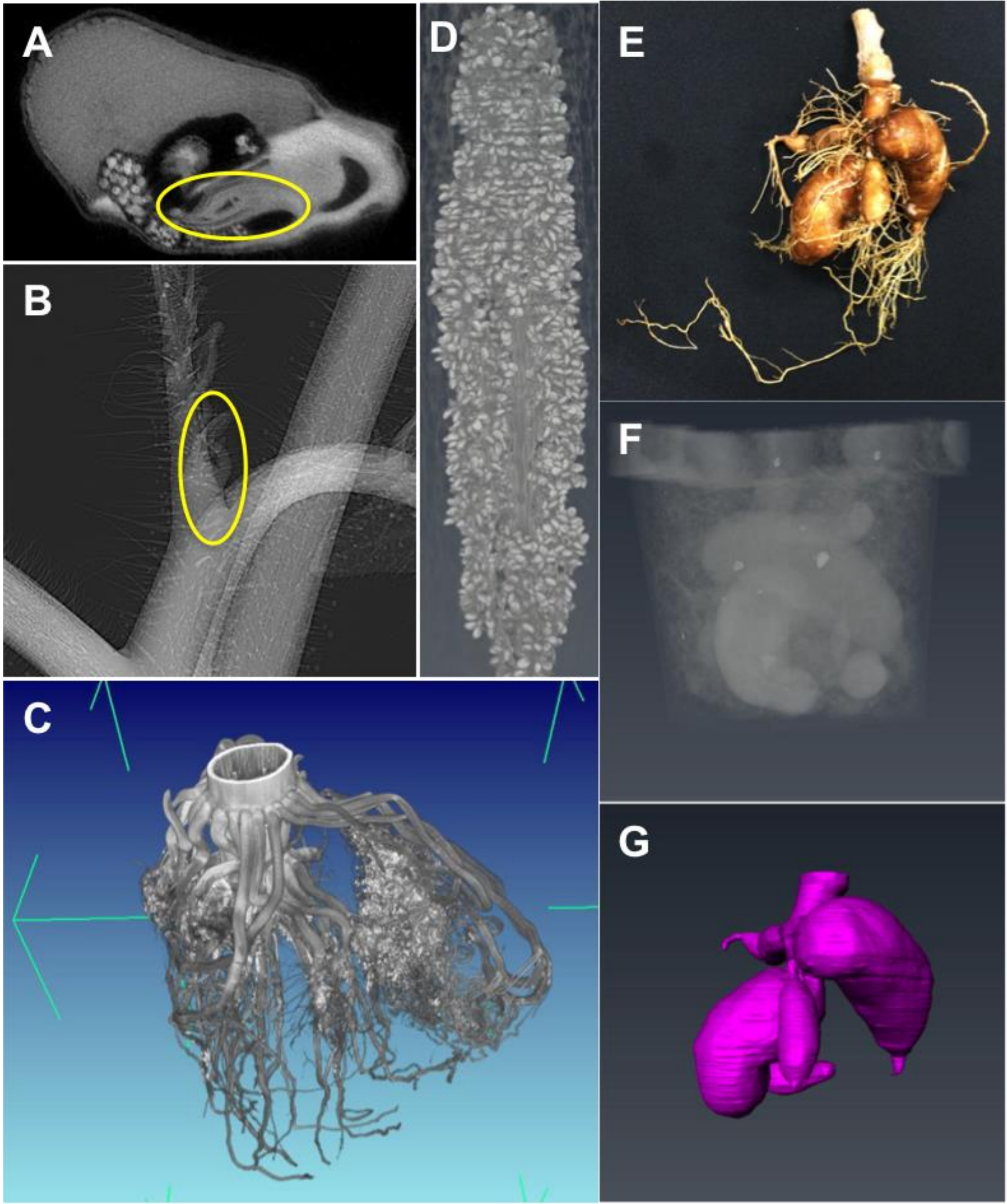
X-ray CT can be used to quantify subterranean biomass in high throughput



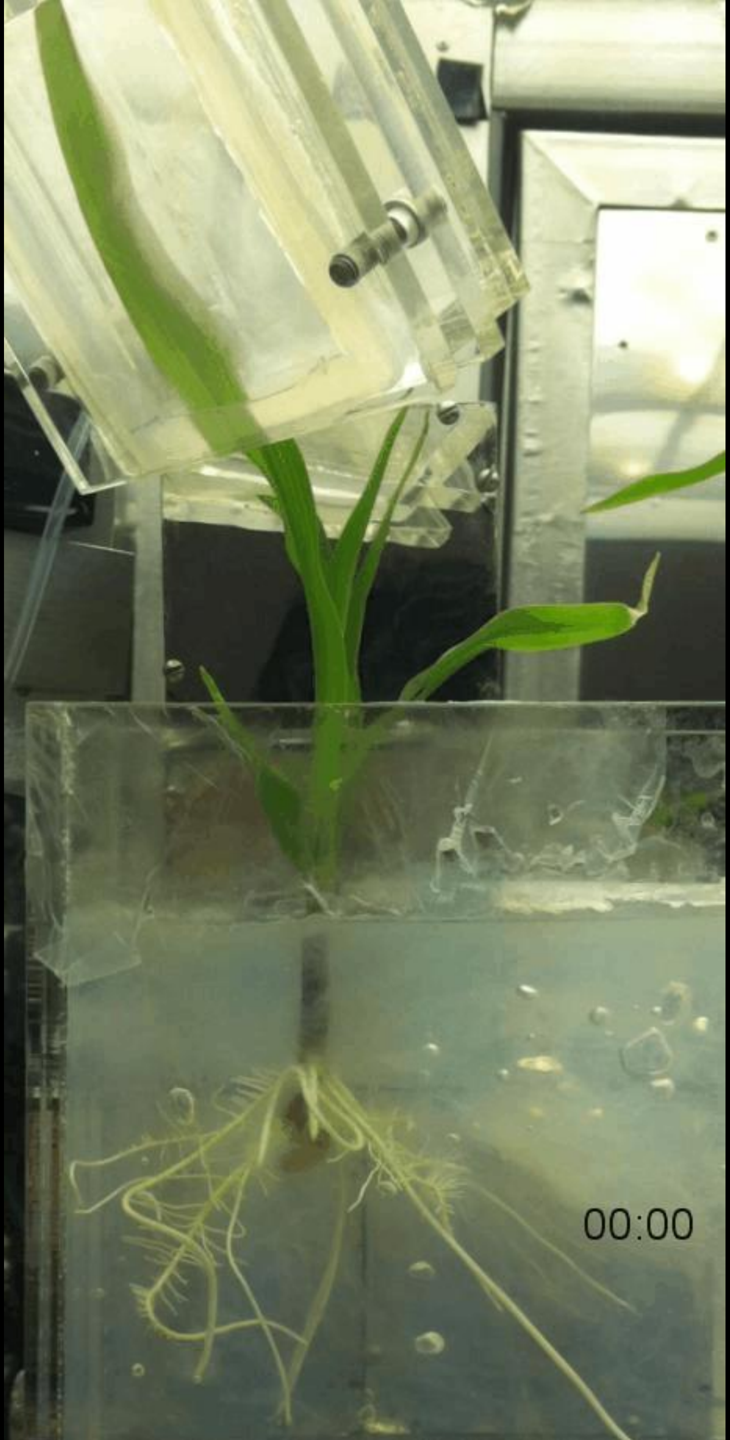
X-Ray CT scanned excavated cassava root| scan time ~ 5 minutes | resolution 110 micron

Volume	Convex Volume	Solidity	Depth	Total Length	# tips
3.6 x 10^6	10 x 10^6	0.3591	285	1792	6

X-ray CT can be used to quantify whole plant morphology through the course of development at micro and macro scales



Positron Emission Tomography (PET): to image whole plant carbon allocation and other dynamic physiological processes



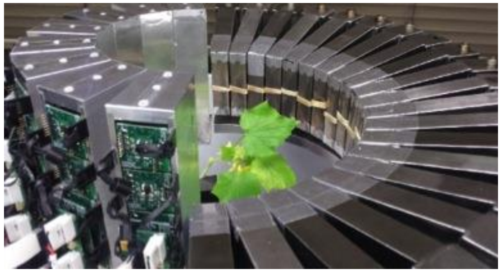
PhytoPET - 2013 IEEE
S. Lee, B. Kross, J. McKisson, J.E. McKisson, A.G. Weisenberger, W. Xi, C. Zorn, G. Bonito, C.R. Howell, C.D. Reid, A. Crowell, L. C. Cumberbatch, C. Topp, and M.F. Smith

Plant PET System

Funded by a **NSF MRI Grant DBI-1040498**

PET imager integrated in a plant growth chamber

A cucumber plant labeled with $^{11}CO_2$



Yuan-Chuan Tai, Qiang Wang, Sergey Komarov,

Aswin J Mathews, Ke Li, Jie Wen,

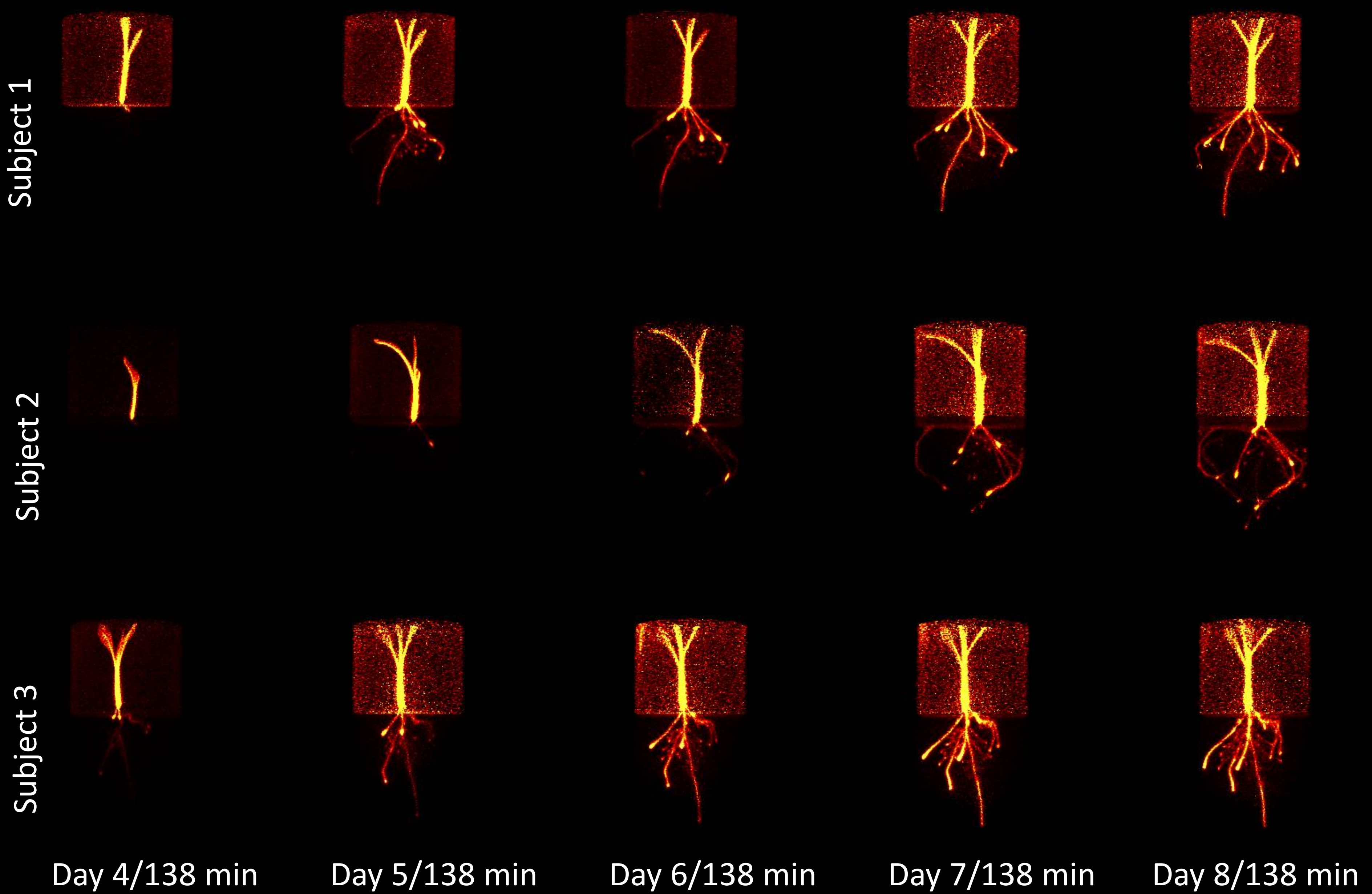
Joseph A O'Sullivan

Washington University

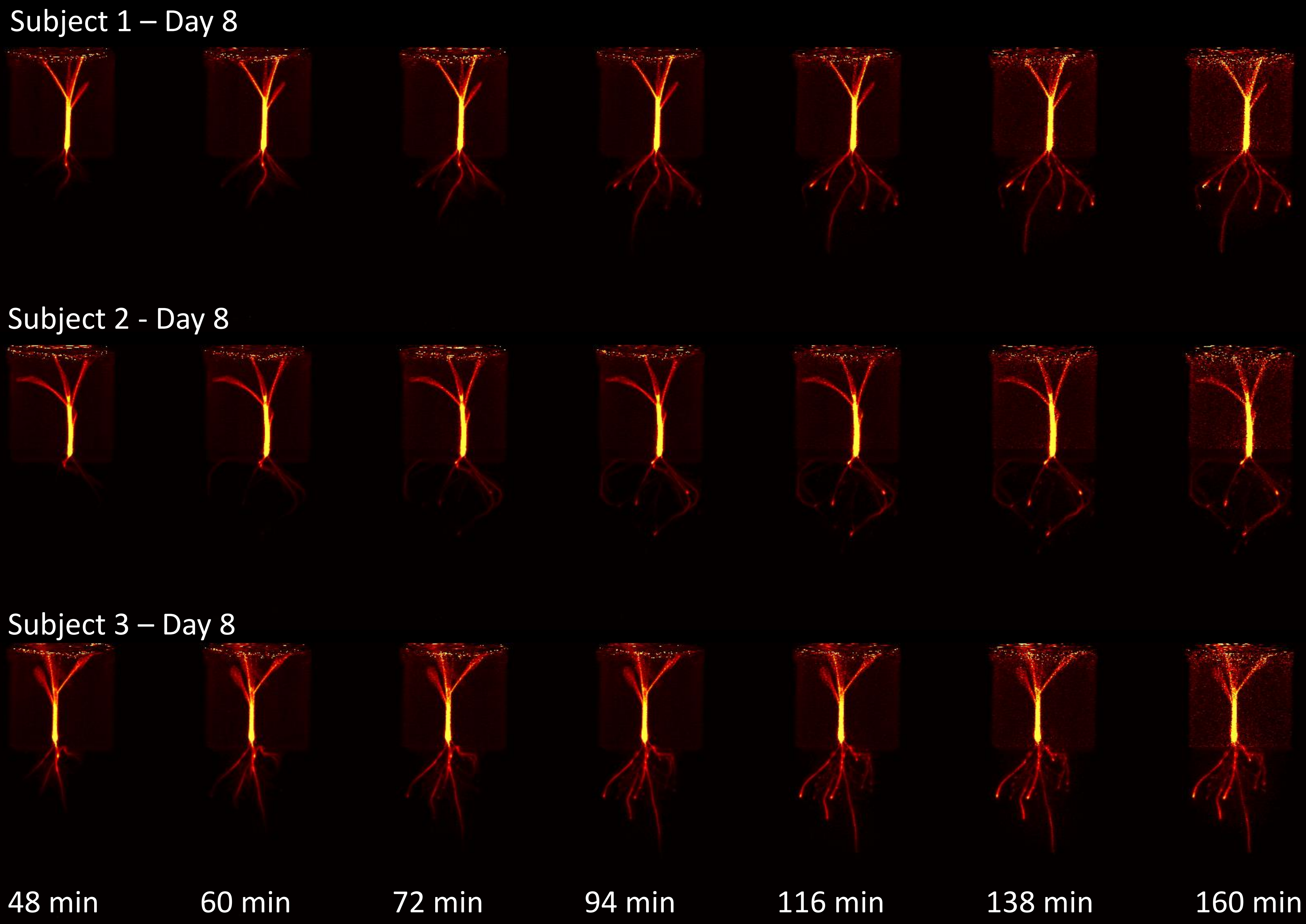
Department of Radiology

Department of Electrical and Systems Engineering

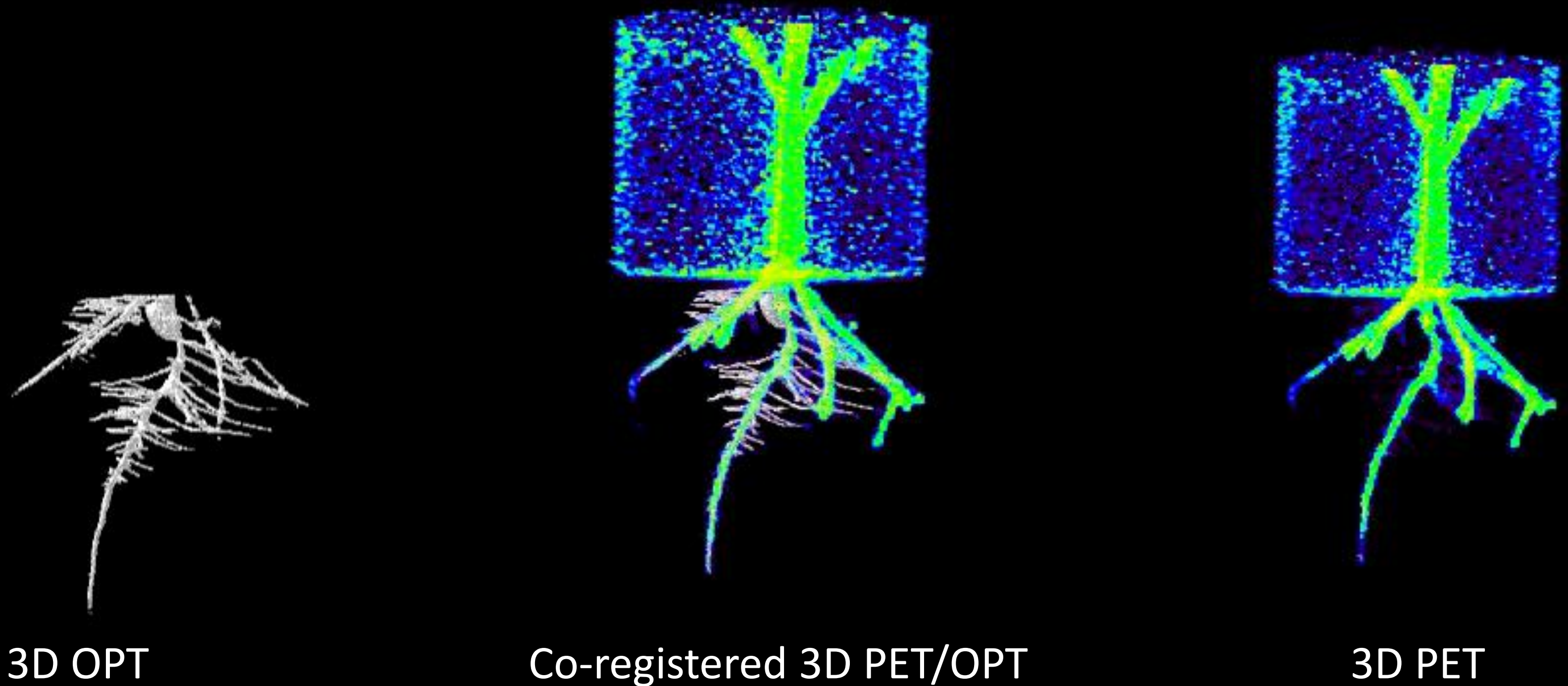
Carbon allocation dynamics can be measured over multiple days of development



Carbon allocation dynamics can be measured in real time

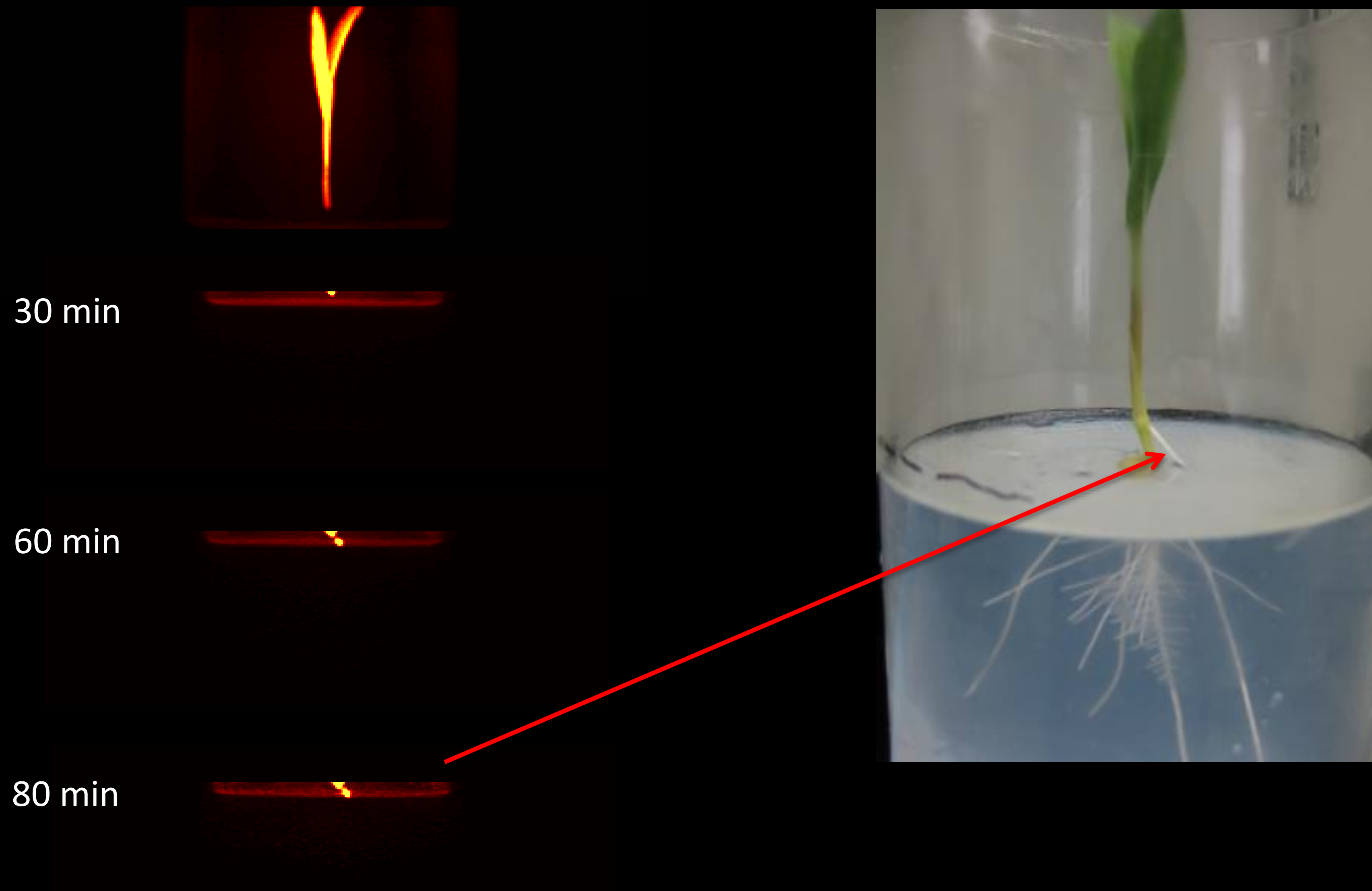


Combined Optical Projection Tomography and PET (OPT-PET) imaging

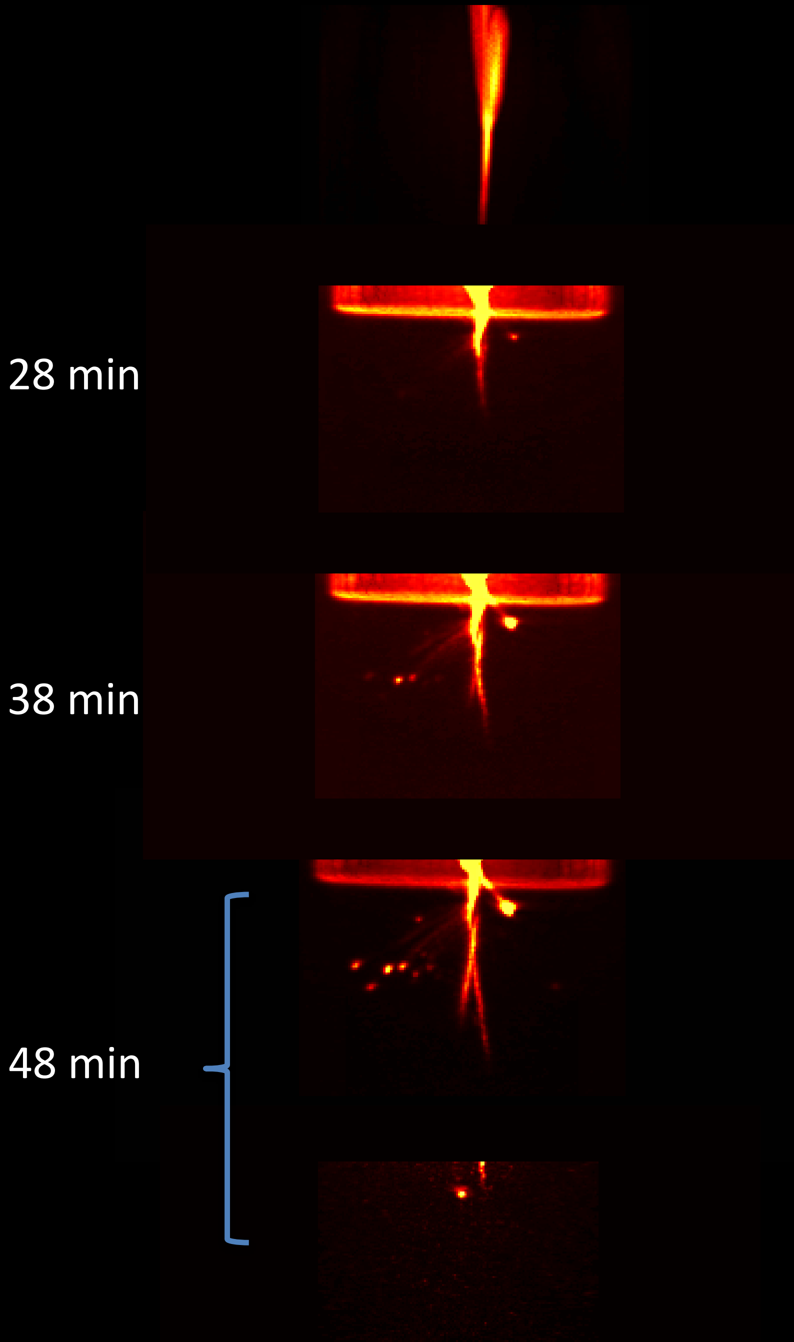


Wang Q., et al. arXiv.org 2015 | Jiang N., Wang Q., Komarov S., Tai Y.-C., Topp C. - unpublished

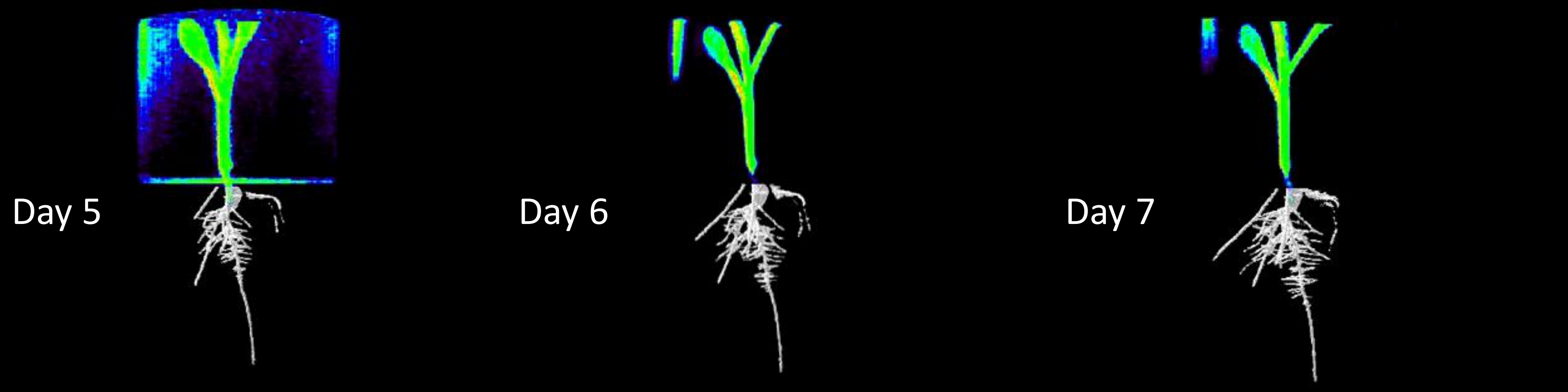
no carbon allocated to seed-derived roots at day 03

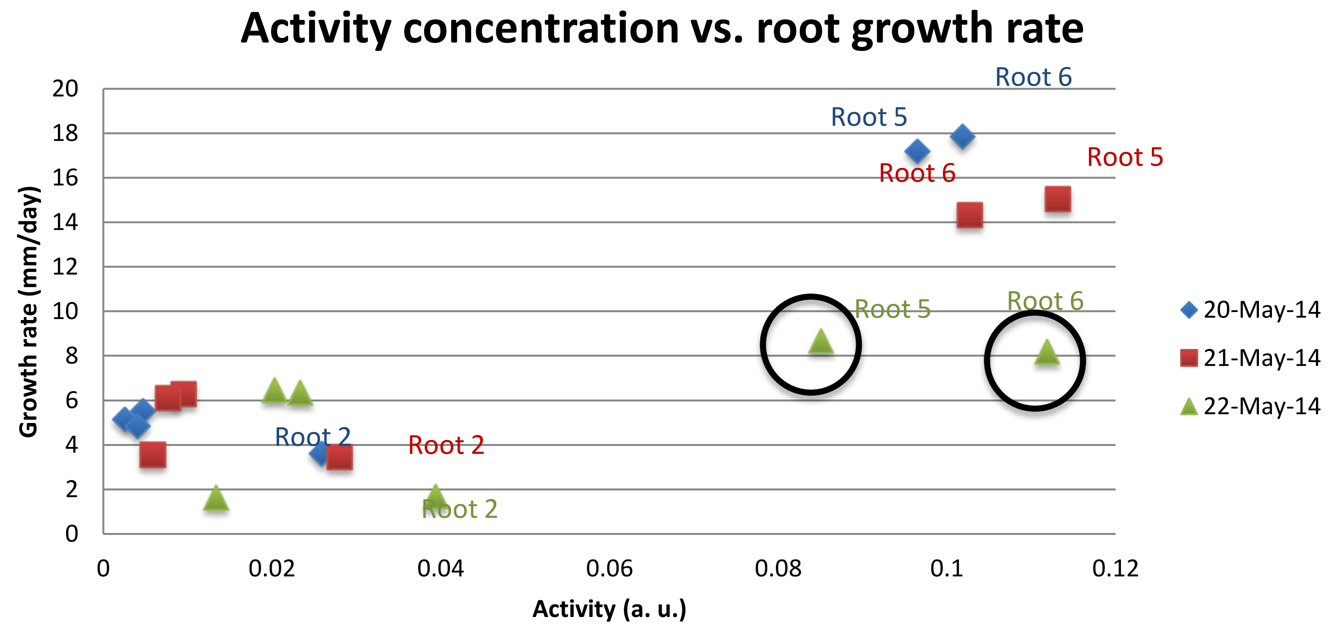


carbon moves to seed-derived roots at day 04



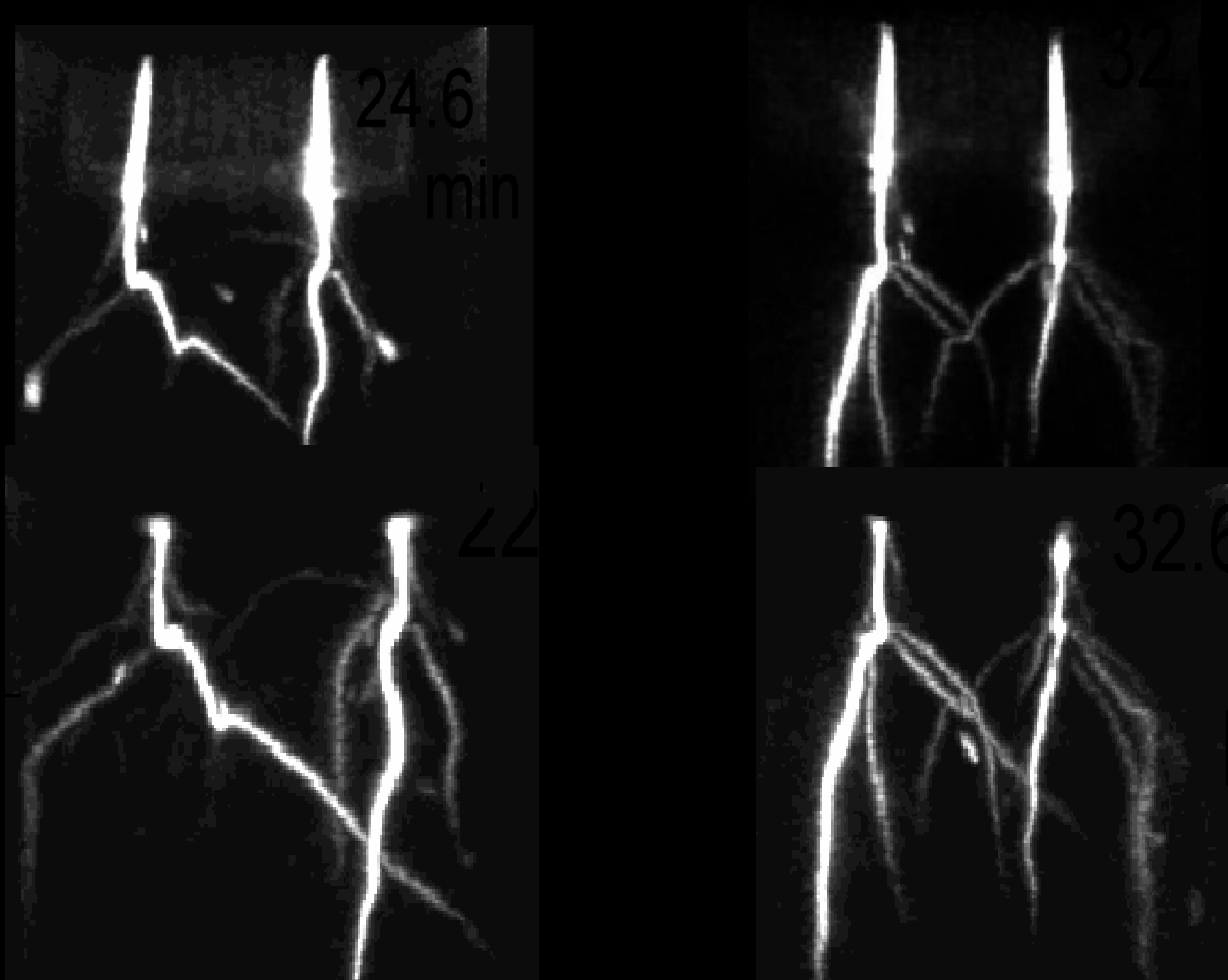
OPT-PET can be used to measure root growth as a function of carbon allocated





Root growth rates are measured from OPT

OPT-PET can be used to quantify root-root and root-microbe interactions



day 06

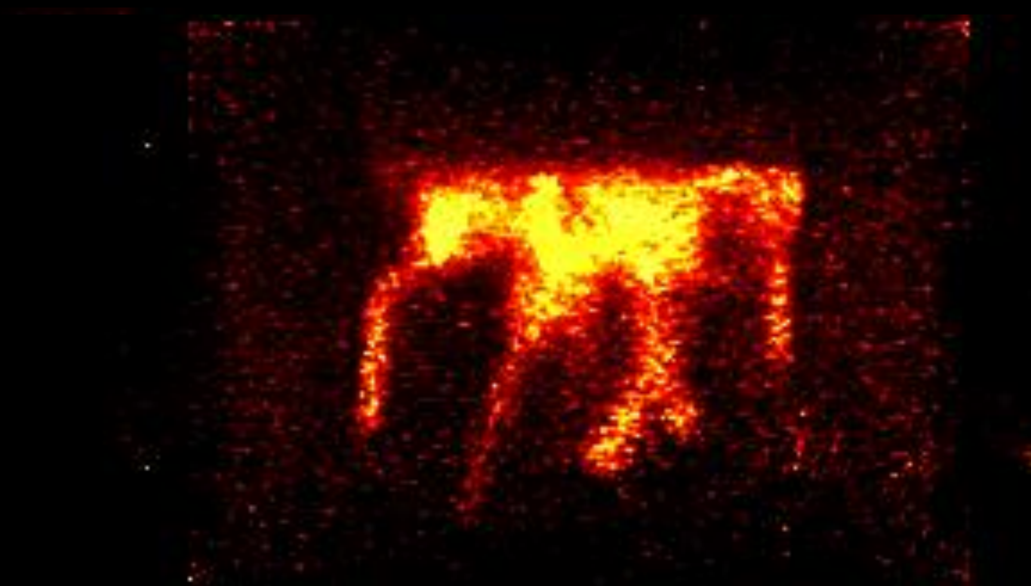
day 07

Unadapted maize

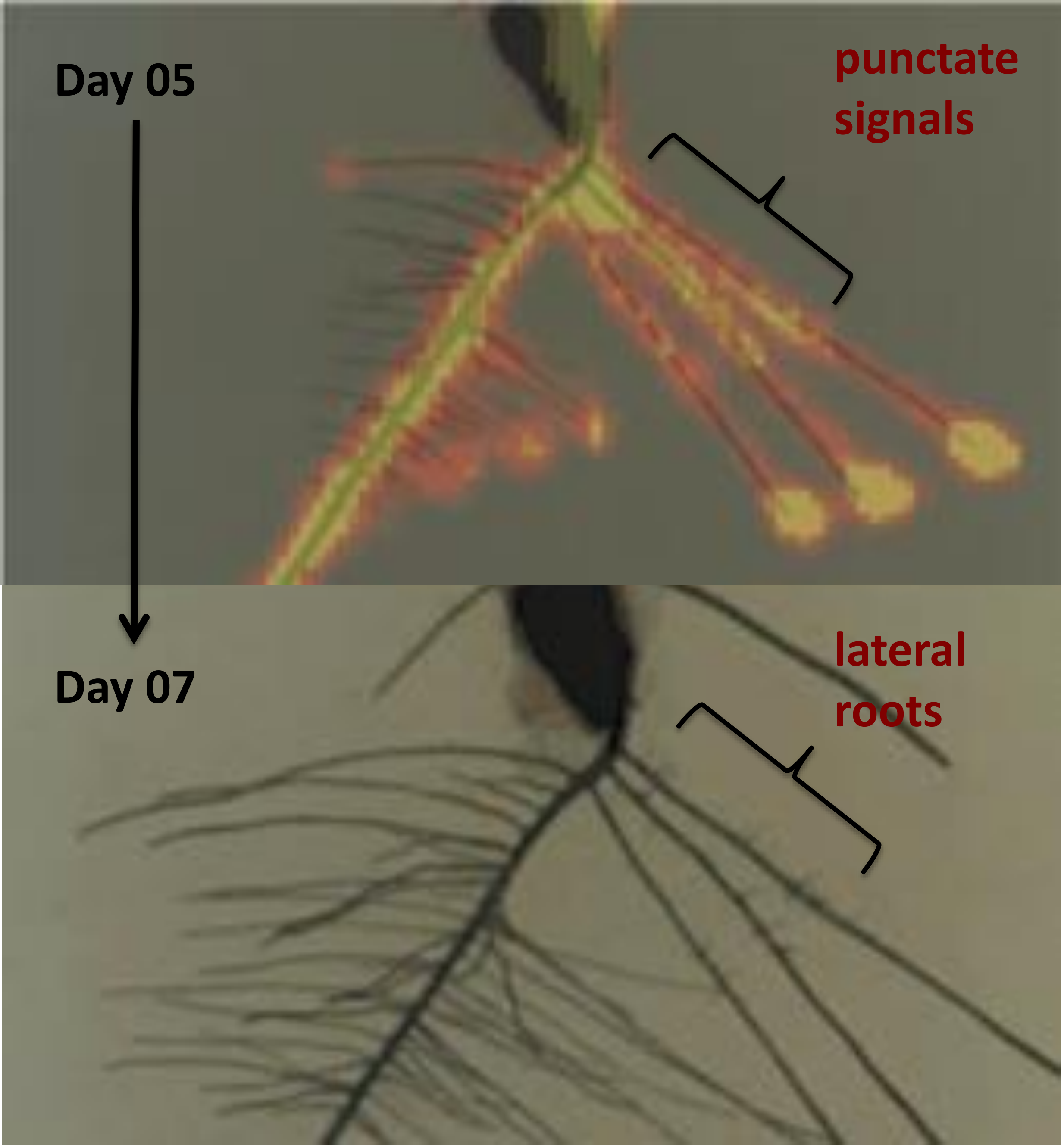
Density adapted maize

OPT-PET can be used to quantify root exudation

with maize plant



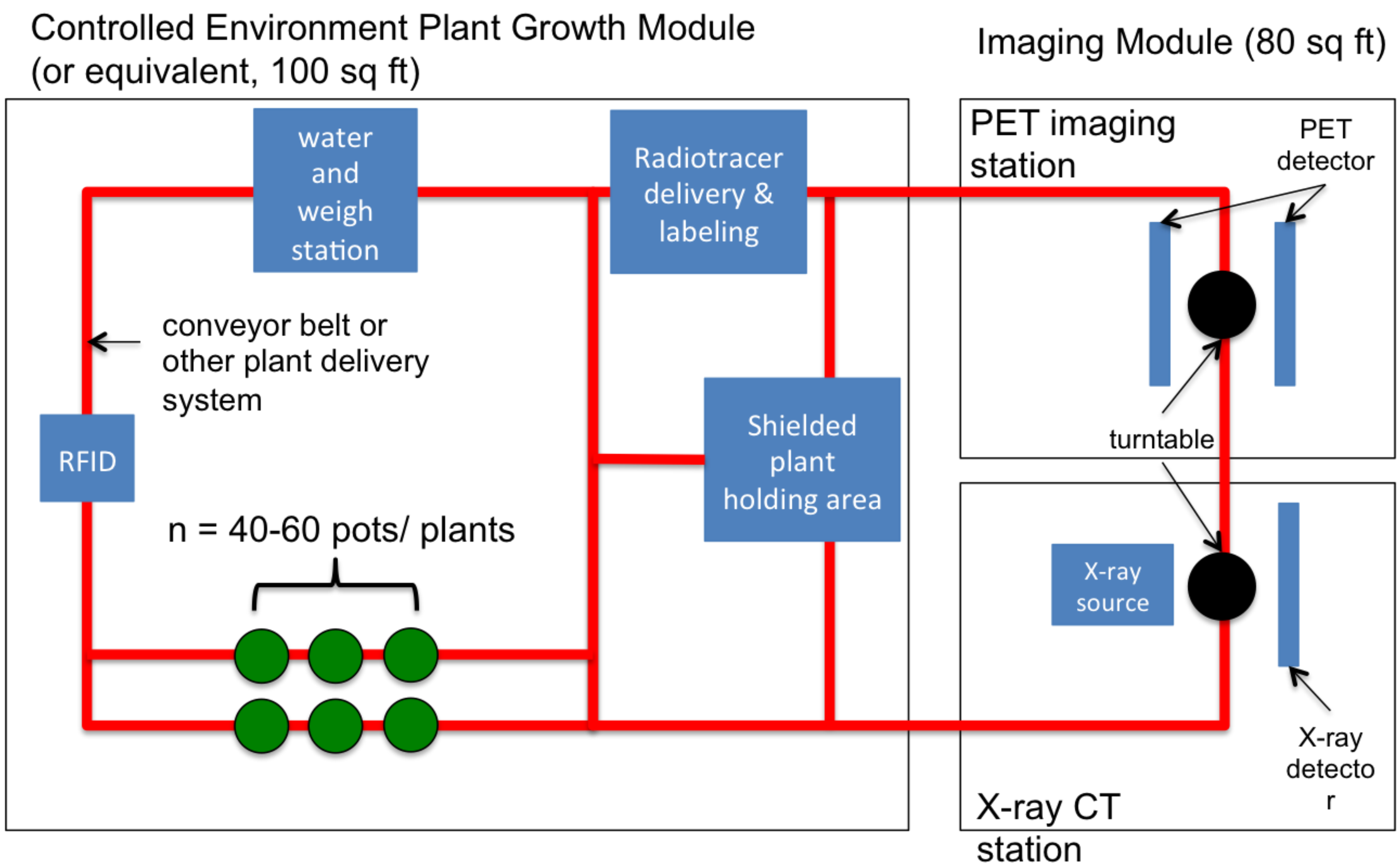
plant is pulled out



OPT-PET: using physiological signals to identify precise spatiotemporal patterns of morphological change

Wang Q., et al. arXiv.org 2015 | Jiang N., Wang Q., Komarov S., Tai Y.-C., Topp C.- unpublished

Proposed XRT-PET plant imager



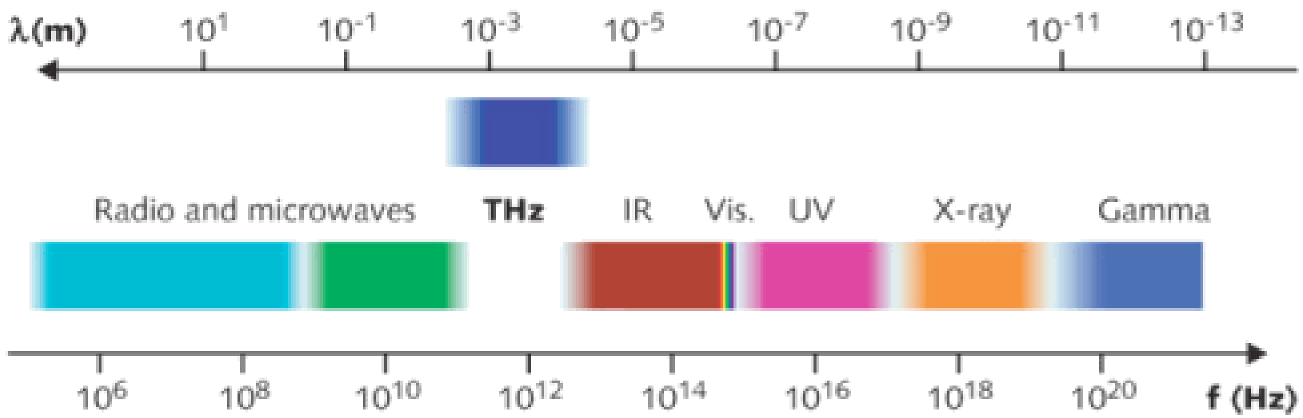
1. fully automated watering, weighing, sample tracking
2. automated PET radiotracer delivery and labeling system
3. PET imaging station(configurable geometry)
4. X-ray CT imaging station(configurable geometry)
5. imaging loop can run independently of water/weigh and radiotracer labeling
6. water/weigh can run independently of imaging loop

How can we move beyond laborious, destructive field root phenotyping?

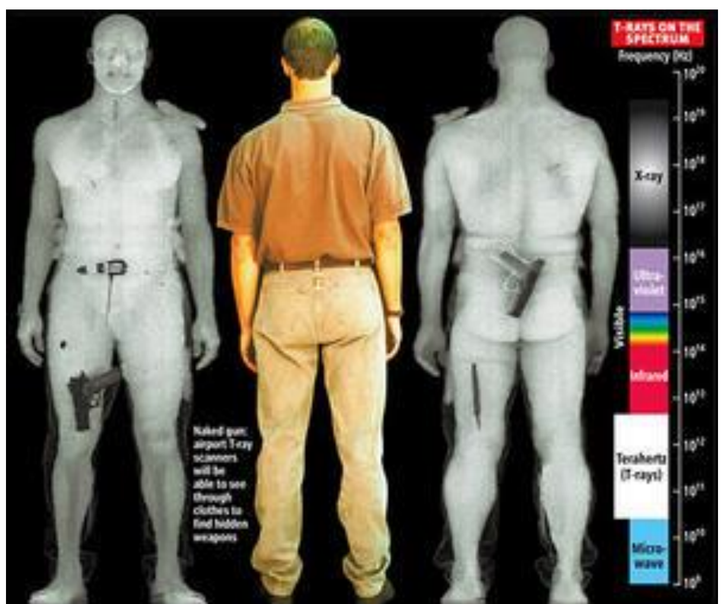
Large-scale minirhizotron mapping in conjunction with shovelomics/DIRT to map root architecture in the field

Project with Andrew Leakey, Ivan Baxter and Steve Moose

Terahertz imaging is an emerging non-destructive evaluation technique that can be used to identify objects of interest that are otherwise opaque in the visible light spectrum



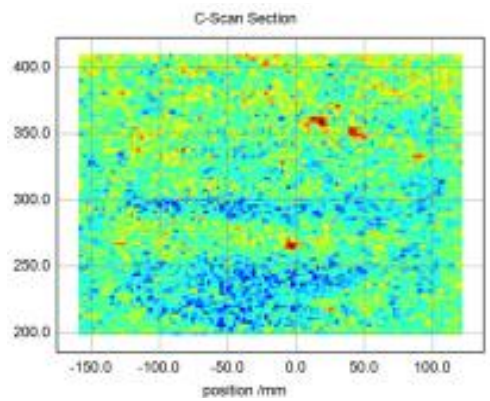
www.laserfocusworld.com

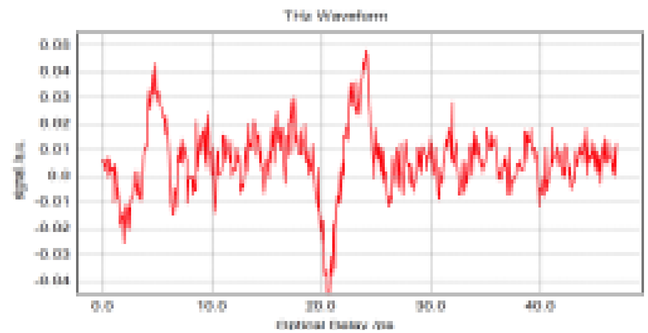


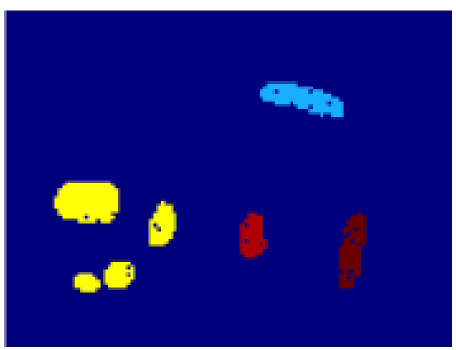
Terahertz scanner imagery // Source: dailymail.co.uk

Towards Root Phenotyping in-situ Using Teraherz Imaging

N. Smith[1], N. Burford[2], L. Rivera[1], T. Bowman[2], M. O. El-Shenawee[2], and G. N. DeSouza[1]
[1]ViGIR - Vision-Guided and Intelligent Robotics Lab, University of Missouri
[2]Terahertz Imaging and Spectroscopy Lab, University of Arkansas



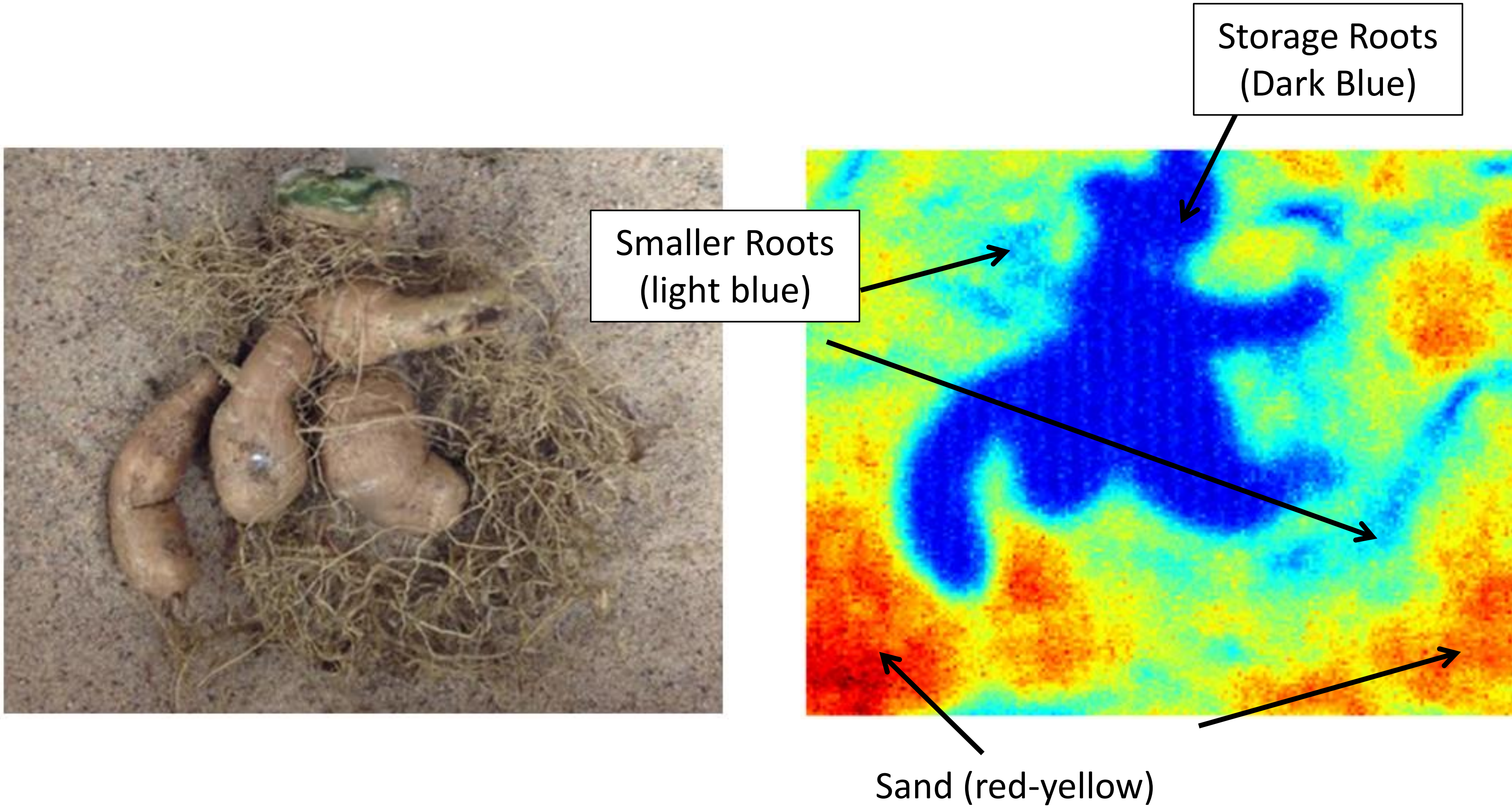




Classification Accuracy %	
Sand+Potato	92.50
Sand+Rock	94.68
Sand+Turnip	91.43
Sand+Wood	87.73

(a) Photo of the samples used for the THz reflection test including a sweet potato, a turnip, four rocks and a piece of tree branch (uncovered to show the objects); (b) Time domain THz reflection image of the objects after being completely buried by dry sand; (c) The time domain reflected signal at a particular point in (b); (d) Final classification using the HiGUSSS Framework

Teraherz imaging of a cassava root system buried in sand



Guilherme DeSouza - University of Missouri-Columbia | **Magda El-Shenawee** – University of Arkansas-Fayetteville | **Felix Fritschi** – UM-Columbia | **Nigel Taylor** – Danforth Center
Chris Topp – Danforth Center

Multidisciplinary Collaborators

Herbert Edelsbrunner Lab @ IST
Olga Symonova

Joshua Weitz @ GA Tech
Alex Bucksch

Yuan-Chuan Tai Lab @ WUSM
Sergey Komorav
Qiang Wang

Dan Goldman Lab @ GA Tech
Daria Moanenkova

Drew Weisenberger @ J-Labs
Seungjoon Lee

Tim Horn @ NC State

Mark Anastasio @ WUSTL
Trey Garcon

Steve Moose Lab @ UIUC

Jode Edwards @ USDA/ IA State

Ivan Baxter Lab @ USDA/DDPSC

Dan Chitwood Lab @ DDPSC

Sherry Flint-Garcia Lab @ USDA/UMC
Zhengbin Liu

Leon Kochian Lab @ Cornell
Randy Clark (Pioneer)

Philip Benfey Lab @ Duke
Anjali Iyer-Pascuzzi (Purdue)

Thomas Mitchell-Olds @ Duke
Jill Anderson (USC)
Cheng-Ruei Lee (GMI)

Special thanks to:
Bruce Hibbard and Tim Praiswater
Martin Bohn and Nicole Yana